Comparison of regional scale burned area products for southwestern Brazilian Amazonia

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Abstract. *Fires affect the Amazon Forest and cause a variety of socioenvironmental problems. Monitoring the dynamic of forest fires is important to support both combatting and preventing wildfires. However, many studies reported discrepancies in the quantification of forests affected by fires, especially in the tropics. In this study, we aimed at assessing four operational burned area products. We defined a study area located in the southwest Brazilian Amazon and selected the year 2019. The assessment focused on evaluating the product's relative performance, stratified by forest and non-forest areas. The four products showed divergence, by up to 90.61% in their estimates of the total burned area (MAPBIOMAS with more extensive burned area mapping and MCD64A1 with more minor burned area mapping).*

Key-words: forest fire, burned area, land use cover change, geospatial analyses

1. Introduction

The human species is the main agent that is transforming natural ecosystems and causing profound changes in the landscape [Berlinck and Batista 2020], especially when associated with fire. The impact of fire in Brazil has increased, especially in recent years [Alencar et al. 2022]. Understory forest fires make the forest more susceptible to future fire events, especially in the Amazon rainforest region where this type of event is naturally rare [Bush et al. 2008]. This scenario can have various consequences for the ecosystem, such as impacts on biodiversity [Mataveli et al 2017, 2021 a,b], economic losses [Mendonça et al. 2004] and climate change [Aragão et al. 2018; Silva Junior et al. 2019; Carvalho et al. 2021; Aragão, Silva-Junior, and Anderson 2020].

Amazon rainforest is an important global climate regulator, acting as a provider of environmental services [Fearnside 2008], including the forest's role as a carbon stock and as a regulator of rainfall in South America [Leite-Filho et al. 2021]. This forest has been faced with deforestation and forest degradation propagated by the fire of anthropic origin, which causes human health problems [Campanharo et al. 2022] and imbalances in the hydrological and carbon cycles [Maraseni et al. 2016; Prentice et al. 2011; Leite-Filho et al. 2021; Shakesby and Doerr 2006]. Therefore, it is important to develop actions to monitor fire-related activities to support measures for preventing and mitigating environmental impacts in the Amazon rainforest [Mataveli et al. 2021 a,b; Andrade et al. 2020].

The use of remote sensing techniques has allowed the development of methodological approaches to detect and monitor burned areas, especially in forest regions [Anderson et al. 2015; Giglio et al. 2018; Shimabukuro et al. 2015; Penha et al. 2020]. These methodologies have several specificities that can achieve different purposes and have different scales and spatial resolutions, leading to different results for the spatial distribution, time, size, and frequency of burned area [Mouillot et al. 2014; Long et al. 2019]. Diversity in mapping creates the need to use a comparison tool among the burned area products because it allows evaluation of the mapping according to performance [Humber et al. 2019; Padilla et al. 2015], especially when there are no field validation points in the region. In this aspect, it is important to understand that comparisons between products have a variety of limitations [Pessôa et al. 2020] and it is necessary to assume that all methodologies are only providing an approximation of the real conditions [Humber et al. 2019]. These comparisons should be used as a complement to the product validation process [Pessôa et al. 2020]. Due to these limitations, the comparison analysis considers the disadvantages and advantages of the products for different purposes [Pessôa et al. 2020; Anderson et al. 2015]. The analyses must be carried out according to the product specifications, and this information must be balanced in choosing the data to be included in the analysis and the final objective of the data use [Pessôa et al. 2020; Long et al. 2019; Boschetti et al. 2020].

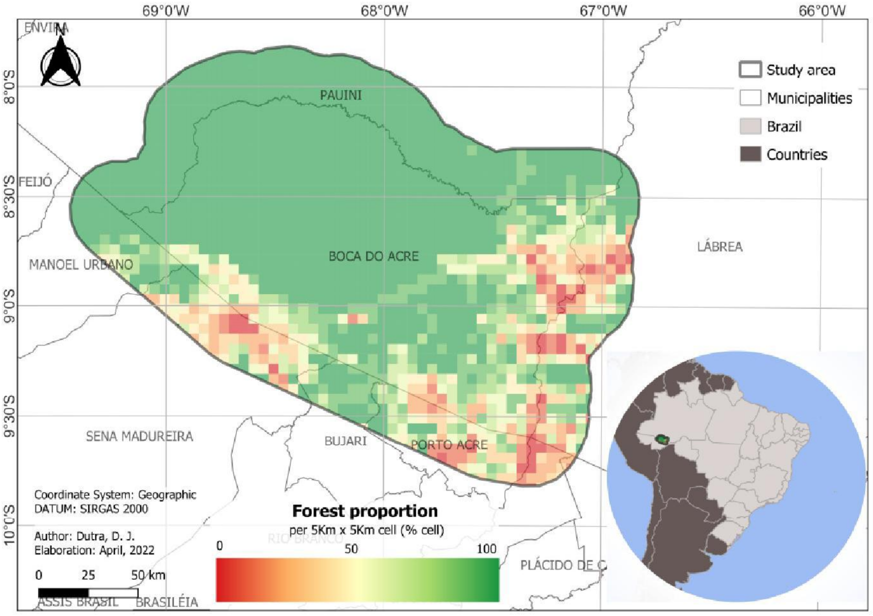
Although several studies have assessed the differences in the results of burned-area products [Penha et al. 2020; Mataveli, Chaves, et al. 2021; Humber et al. 2019; Anderson et al. 2015; Pessôa et al. 2020], their inter-comparison suggests a spatially heterogeneous performance, which means that a prior evaluation of a site should be carried out before selecting a product. Here we assessed four operational burned-area products [MAPBIOMAS, MCD64A1, GABAM, and GWIS] for the southwest Brazilian Amazon – a region increasingly under threat of fires. The specific objectives were: (i) to evaluate the similarities and differences among operational burned-area products in forest and non-forest areas in the municipality of Boca do Acre, state of Amazonas, and (ii) to analyze the spatial similarities and differences between the products.

2. Materials and Methods

2.1 Study area

The study area focus on Boca do Acre Municipality, the State of Amazonas, including a buffer of 25 km around the, covering a total area of 40,777 km². The buffer area covers parts of the municipalites of Paiuni (19.42%), Lábrea (5.42%), Acrelândia (1.91%), Senador Guiormard (16.16%), Porto Acre (79.01%), Bujari (28.18%), Sena Madureira (9,58%) and Manoel Urbano (13.68%). The area encompasses portions of seven indigenous territories: Camicua, Igarapé Capana, Inauini/Teuiní, Boca do Acre, Apurinã, Peneri/Tacaquiri, and Seruini, Mariene, and five conservation units (protected areas for biodiversity): Mapiá-Inauiní National Forest, Purus National Forest, and the Arapixi Extractive Reserve. According to PRODES data for 2019 [Assis et al. 2019], the regions contain 33,335.80 km² of forest (Figure 1), characterized by dense rainforest

(Amazon Forest), mosaics of oligotrophic woody vegetation, and ecotone areas [Barni et al. 2015] with Köppen classification system of Af (equatorial forest climate) [Alvares et al. 2013].



. **Figure 1 - Study area located in the Boca do Acre, municipality, state of Amazonas. Forest proportion in a 5x5 km grid cell, extracted by the Amazon Forest Deforestation Calculation Program (PRODES) forest mask of 2019 used to select burned areas**

2.2 Data

We considered three global burned area products (MCD64A1 [Giglio et al. 2018], GABAM [Long et al. 2019], and GWIS [Boschetti et al. 2020]) and one national product MAPBIOMAS [Arruda et al. 2021]) for the comparative evaluation of burned area detection (Table 1). The choice of products took into account the spatial scale to compare products and analyze the influence of increased resolution in burned-area detection. For this, we used one low-resolution product that has been widely used in the literature (MCD64A1), one product in vectorial format (GWIS) and two products, with higher spatial resolution (30 m: MAPBIOMAS and GABAM). The year 2019 was selected for this analysis.

Table 1 - Specifications of the burned area products.

Name	Developer	Scale	Temporal Scale	Sensor/Data	Spatial resolution	Reference
GABAM	Institute of Remote Sensing and Digital Earth—Chinese Academy of Sciences	Global	1985-2020	Landsat series	30m	(Long et al. 2019)
GWIS	Group on Earth Observations (GEO) and Copernicus Work Programs	Global	2001-2020	MCD64A1, MODIS, Copernicus-Proba-V and Fire CC1	Vector data	(Boschetti et al. 2020)
MAPBIOMAS	MAPBIOMAS	National (Brazil)	2000-2020	Landsat series	30m	(Alencar et al. 2022; Arruda et al. 2021)
MCD64A1	NASA	Global	2000-present	MODIS (surface reflectance and active fires)	500m	(Giglio et al. 2018)

2.3 Analysis

We calculated the total burned area estimated by each product in the vectorial analyses, with separation by class in the whole study region. For this, the PRODES land-cover data from 2019 [Assis et al. 2019] were used to separate the landscape class into forest and non-forest. In the process, we used the SQL command and PyQGIS (gdal library) in QGIS 3.22.6 software (Qgis 2019) and the 'rgeos' package [Bivand and Rundel 2018] in RStudio statistical software [R Core Team 2021]. Furthermore, we created a regular grid with a spatial resolution of 25 km² (5 km × 5 km) for the matrix analysis of burned-area products. In the process, we considered the proportion of the burned area detected by each product per grid cell. The grid tools and SQL commands in QGIS software were used to process the data in the system.

Regarding the statistical analysis, we executed the non-parametric Kolmogorov–Smirnov two-sample test [Smirnov 1939] to compare the six possible combinations between the burned-area products. For this, we used the 'raster' package [Hijmans 2017] of RStudio software [R Core Team 2021]. We used conditional, repeating structures in a bootstrap approach to creating 10,000 interactions of 10% of the total cells that were randomly selected with replacement in each execution of the conditional structure. In this process, we considered only cells that presented burning detection by at least one. Finally, we considered the mean and standard deviation of the 10,000 p-values resulting from the interactions. For the spatial analyses, we converted the regular grid to raster format with information on each burned area, including a two-by-two statistical comparison using the fuzzy numerical method implemented in the "calc reciprocal similarity map" functor [Dinamica EGO Team 2020] of DINAMICA EGO 6 software [Leite-Filho et al. 2020]. The fuzzy method analyses used the spatial similarity between pairs of cells in two numerical maps, using the neighborhood (window size of 3 lines by 3 columns) to calculate the similarity of each cell [Dinamica EGO Team 2020]. Furthermore, the value interval of results is between 0 (fully distinct) and 1 (fully identical).

3. Results

We detected a total of 7167 km² burned area mapped in 2019 by the products in the study area, of which 264 km² (3.69%) was in the forest area and 6903 km² (96.31%) was in the non-forest area (Figure 2). In forest areas, GWIS and MCD64A1 detected the quantified larger extent: 90 km2 (33.93%) and 100 km² (37.95%), respectively. In the non-forest areas, GABAM and MAPBIOMAS detected a larger extent of 3111.18 km² (45.07%) and 3338.98 km² (48.37%), respectively.

The burned area (Figure 3) showed the greatest difference occurring between MAPBIOMAS and MCD64A1, where MCD64A1 mapped 90.61% (3062 km²) less burned area in comparison with MAPBIOMAS. Compared to MCD64A1, MAPBIOMAS detected a 30.43% larger area 3122.33 km²) of burned in the non-forest area and a 30.43% smaller burned area (60.33 km²) in the forest area. Two of the products (GWIS/MCD64A1 and GABAM/MAPBIOMAS) produced very similar results. MCD64A1 detected only 2.46% (8 km²) less total burned than GWIS, but detected more burned area in the forest class (4.02% or 100.2 km²) and less burned area in the non-forest class (4.02% or 29.1 km²). MAPBIOMAS detected 6.93% (234 km²) more total burned area than GABAM, which detected 8% (228.72 km²) in non-forest areas and 8% (5.27 km²) in forest areas. The GWIS and MCD64A1 showed non-significant differences at a 95% confidence level ($p > 0.05$), Table 2. In this process, the bootstrap approach resulted in 99,37% of 10000 interactions was non-significant (p >

0.05). Other combinations among the burned area products present 100% significant p-values at a 95% confidence level ($p < 0.05$).

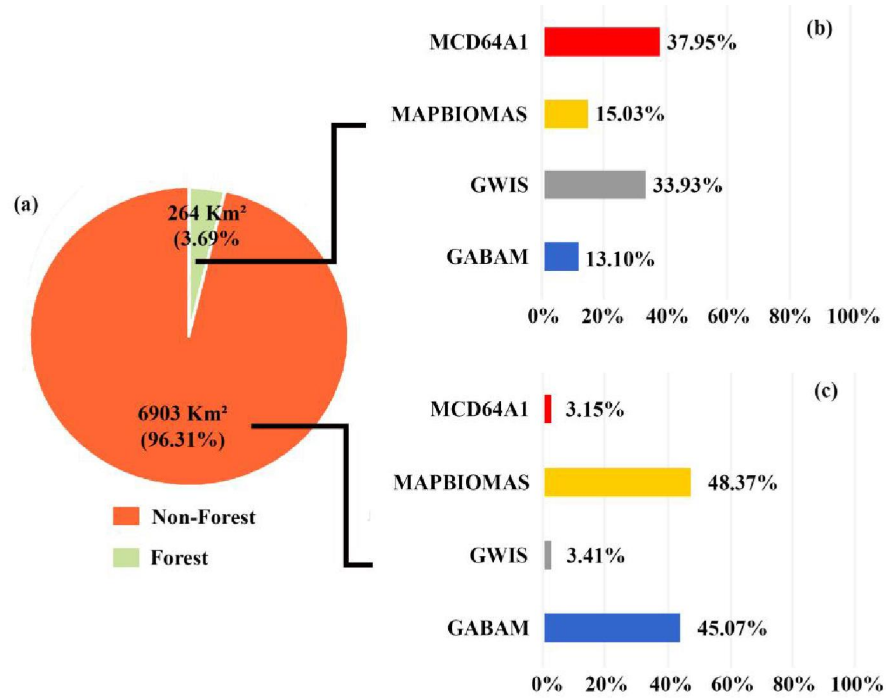


Figure 2 - (a) percentage of the total burned area detected by any of the products that are in forest and non-forest. (b) Percentage of the area classified as burned by each product in the forest area, and (c) Percentage of the area classified as burned by each product in the non-forest area.

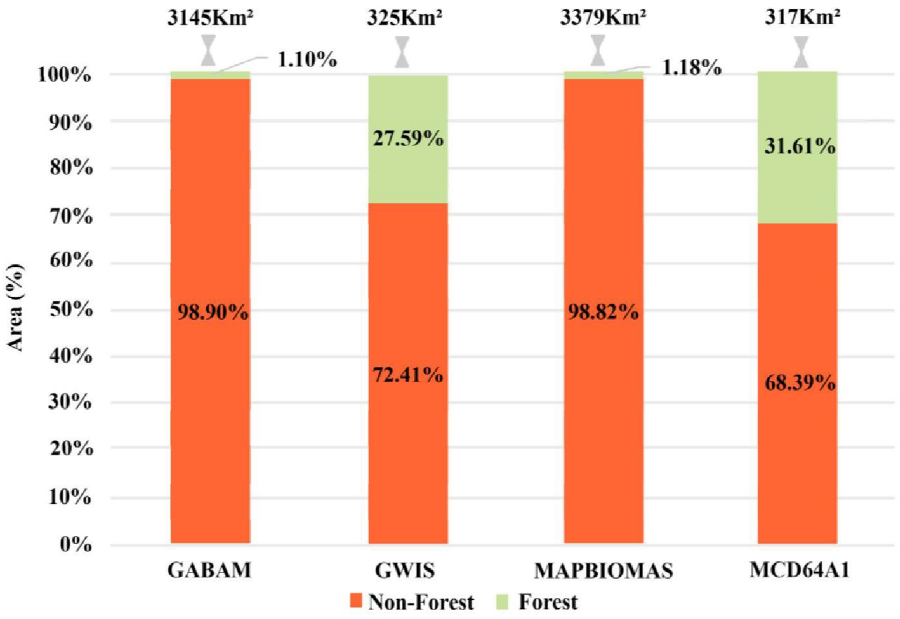


Figure 3- Total burned area mapped by GABAM, GWIS, MAPBIOMAS, and MCD64A1 and percentage burned area in the forest and non-forest classes.

Table 2 - Mean and standard deviation of p-values resulted from 10,000 iterations of Kolmogorov- Smirnov two-sample tests, raffling different samples of 10% of the total grid cells of 25 km².

	GABAM X GWIS	GABAM X MAPBIOMAS	GABAM X MCD64A1	GWIS X MAPBIOMAS	GWIS X MCD64A1	MAPBIOMAS X MCD64A1
Mean	6.97E-05	3.22E-05	1.04E-04	2.40E-08	5.94E-01	3.13E-08
Sd	2.96E-04	6.24E-05	3.18E-04	5.27E-07	2.91E-01	1.67E-07

Regarding the spatial analysis, the four products showed divergence, mainly in the northeast region of the study area that contains the largest presence of forest (Figure 4). Among the four products, MAPBIOMAS mapped the greatest amount with burned-cell proportions between 20% and 50% in grid cells (Figure 5). Compared with GABAM, with the same spatial resolution, the MAPBIOMAS project identified a greater number of burned cells in the range from 1.475km² (59 grid cells) to 110.975km² (4439 grid cells).

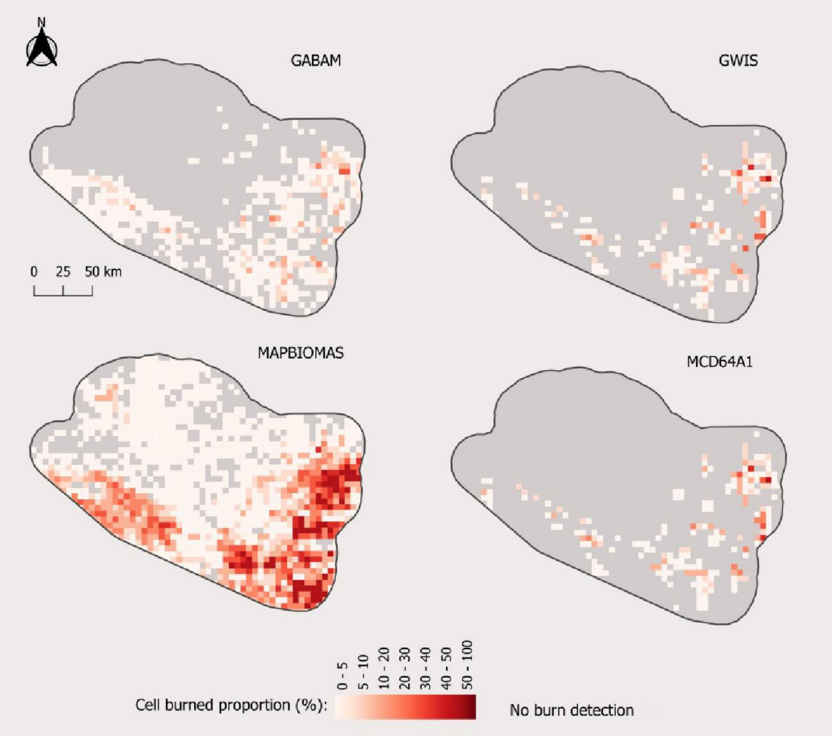


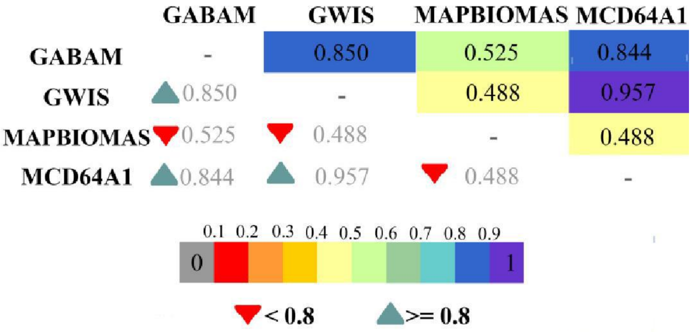
Figure 4 - Burned area spatialization in a 5 km × 5 km regular grid. Each grid cell contains the burned proportion indicated by the color gradient.

Number of cells in different burned area proportion class in a grid of 5km x 5km

	0 - 5	5 to 10	10 to 20	20 to 30	30 to 40	40 to 50	>50
GABAM	443	57	22	3	2	0	0
GWIS	137	42	21	6	5	1	1
MAPBIOMAS	4882	2075	2351	1619	1223	724	59
MCD64A1	128	32	25	8	3	2	1
Total	5590	2206	2419	1636	1233	727	61

Figure 5 - Number of cells in different burned proportion class

We identified that the similarity index was medium to high (≥ 0.8) between the burned area products (Figure 6). Considering the whole study area, the results present values from 0.4 to 0.95. In the results, we observed a pattern of lower values of the similarity index when MAPBIOMAS is considered in comparison with the other products. These results can be explained by MAPBIOMAS presenting the largest extent of mapped burned area, which allows identifying burned areas that other products did not map. The other products presented higher similarity due to the reduced extent of the burned area mapped, which makes them more likely to be similar during the analysis.



	GABAM	GWIS	MAPBIOMAS	MCD64A1
GABAM	-	0.850	0.525	0.844
GWIS	▲0.850	-	0.488	0.957
MAPBIOMAS	▼0.525	▼ 0.488	-	0.488
MCD64A1	▲0.844	▲ 0.957	▼ 0.488	-

Figure 6 - Overall similarity for each burned area product comparison pair, considering the whole area

Spatially, the similarity varied with values between 0 and 1 (Figure 7). This analysis allows the identification of more cohesive areas, or not, since the similarity indices only registered the general average of the region. We identified the lowest values when MAPBIOMAS is considered in the analysis. In this process, the southeastern portion of the study area showed lower values between 0.7 and 0.9, and the northwest present higher values in this interval. The opposite relationship occurs with the other products, which demonstrate higher values in the southeastern portion of the study area.

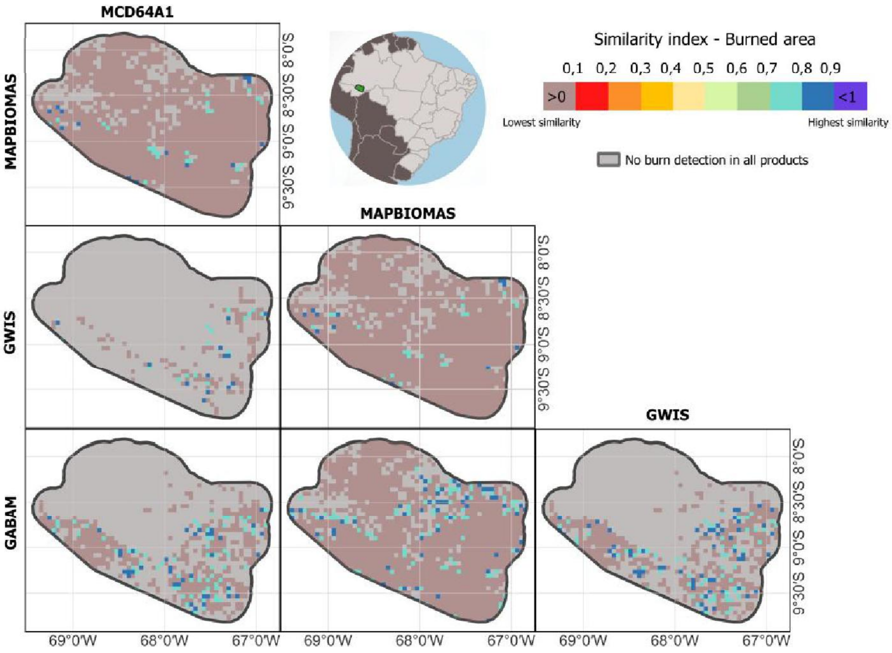


Figure 7 - Similarity maps for each burned area product comparison pair

We observed that MAPBIOMAS registered a low similarity index, mainly in the northwestern portion of the study area, where the product showed the best performance compared to the other products, and identified burned areas in the eastern and southeastern portions of the study area. In this analysis, we found that MCD64A1 and GWIS showed the burned area in the same portions of the study area as the other products, mainly in the eastern portion (Figure 8b). In contrast to GWIS and MCD64A1, GAMBAM presents many burned areas in the same portions of the study area as MAPBIOMAS, especially in the southwestern portion (Figure 8a). Regarding the scale resolution, for the GWIS and MCD64A1 products (lower resolution), the detected areas were mainly in patches in the eastern and southeastern portions of the study area near the edges of the study area. The high-resolution products (GABAM and MAPBIOMAS) identified more burned areas, mainly in the forest region (located in the northeastern portion of the study area), and presented the same burned areas as the other products in the eastern and southwestern portions of the study area.

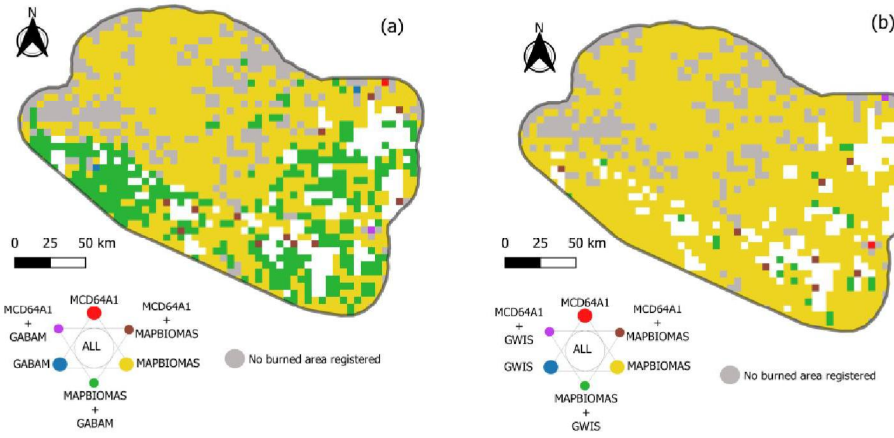


Figure 8 - Confusion maps considering (a) the GABAM, MCD64A1, and MPBIOMAS burned-area products, and (b) the GWIS, MCD64A1, and MPBIOMAS burned-area products

4. Discussions

Our results showed the importance of users understanding the characteristics of the burned area to choose the most appropriate product for their analyses, since each burned-area product may present a significant impact on the final result in studies at different scales, especially on regional scales. This is due to the characteristics and specifications that affect performances regionally, such as daily temporal resolution, spatial resolution, climatic conditions, and the algorithms themselves [Pessôa et al. 2020].

Regarding the mapping of burned areas, we identified two similar groups: GWIS/MCD64A1 and GABAM/MAPBIOMAS. Although the MCD64A1 product showed 2.46% to 90.61% less total burned area compared to the other products we analyzed, this product detected the most burned forest: 10.51% to 65.47% more than other products. Although some studies have shown that MODIS data can underestimate burned area by approximately 25% as compared to Landsat data [Morton et al. 2011; Roy and Boschetti 2009; Pessôa et al. 2020], we identified, on a municipality scale, that MAPBIOMAS and GABAM (Landsat data) generally underestimated burned scars, especially in forest areas, when compared to MCD64A1 and GWIS (MODIS data). However, underestimation of burned area in products that use MODIS data as a reference was identified in non-forest regions, since MAPBIOMAS and GABAM data registered an increase of 92,95% to 93,50% in the burned-area mapping compared to MCD64A1 and GWIS. These differences can be associated with the spatial resolution of the data sources [Long et al. 2019].

We found that the characteristics of mapping can be delimited by different quantities of the burned area detected at regional scales. The high temporal resolution of MODIS data (used for MCD64A1 and GWIS), allows for greater data acquisition and less interference from clouds [Alonso-Canas and Chuvieco 2015; Pessôa et al. 2020], allowing the burned area date to be identified [Bush et al. 2008]. Thus, the frequency of MODIS data identifies the time elapsed since burning and the speed at which vegetation regenerates after the fire, these being important factors for monitoring tropical regions because the higher temporal frequency minimizes the effect of cloud cover and climatic conditions. This product has therefore been widely used in burned-area detection across the globe [Giglio et al. 2018; Justice et al. 2002]. The temporal resolution of Landsat data (used by GABAM and MAPBIOMAS) is 16 days, but the spatial resolution in the optical spectrum is higher (30 m). The higher spatial resolution from Landsat allows an improved definition of the boundaries of burned areas because these features avoid a mixture of burned and unburned patches in the same pixel [Long et al. 2019; Arruda et al. 2021].

We identified that this process can be overestimated when using national-scale products (MAPBIOMAS). The results demonstrate that MAPBIOMAS registered 11 times more burned area with small proportions when compared to a global product with the same resolution (25-km^2 grid cells). According to the developers of GABAM [Long et al. 2019], the overestimated values in the use of Landsat data can be associated with temporal resolution and cloud contamination [Long et al. 2019], which can become a limitation in tropical regions, where cloud cover is persistent and the vegetation recovery is quick. Regarding the MAPBIOMAS data, the developers recommend making some adjustments to the algorithm before applying multitemporal analysis in regions other than the Cerrado, which demonstrates that these data still need to be studied in tropical regions [Arruda et al. 2021].

Overestimation in MAPBIOMAS data may be associated with the application of the Deep Neural Network (DNN) methodology, which, according to the density of training samples per Landsat WRS-2 path/row map created by the product's developers, the study region is located in a scene where there was an intermediate separation of samples [Alencar et al. 2022]. Since the DNN uses pattern recognition to execute the algorithm [Safi and Bouroumi 2013; Langford, Kumar and Hoffman 2019], the low number of samples from the region may have helped in the overestimated result and reinforces the issues that in tropical regions adjustments are necessary for the product algorithm [Arruda et al. 2021]. In addition, we found that comparisons between MCD64A1 and GABAM data showed differences at a municipality scale when compared with the results of analyzes at a regional scale by the developers of MAPBIOMAS [Alencar et al. 2022]. Therefore, the use of images with lower resolution for mapping burned areas can be useful because these products have a higher temporal frequency and less influence on cloud cover [Giglio et al. 2018].

Regarding, the lower resolution products, such as MCD64A1 and GWIS, studies demonstrate that they are unable to adequately detect small fires (< 100 ha) [Rodrigues et al. 2019], which can cause the burned area to be underestimated [Giglio et al. 2018;

Justice et al. 2002], as we found in our results. Despite MCD64A1 presenting a significantly better detection of small burns (< 100 ha) than older products [Pessôa et al. 2020; Justice et al. 2002; Chuvieco et al. 2018], we found the underestimates of the burned area to be from 89.9% to 90.61% as compared to the high-resolution products (30 m). Therefore, GABAM and MAPBIOMAS detect small burned areas better, showing small burn proportions (associated with small burned patches) in the grid with 5-km × 5-km cells.

We observed different patterns when compared with similarities that can cross-validate each other through spatial analysis. We also identified the potential of the MAPBIOMAS product for mapping burned areas, although, for tropical regions such as the Amazon rainforest, future adjustments will be required, as described by the developers [Arruda et al. 2021]. Thus, in the absence of a national product that doesn't require adjustment in the algorithm, the global products still prove to be reliable for operationalization and analysis of socio-environmental loss related to tropical forest fire [Barlow et al. 2020].

5. Conclusions

A comparison of burned-area products allowed us to analyze the influence of spatial resolution in burned-area analysis at the regional scale. Accounting for the magnitude of difference, GWIS and MCD64A1 are the most similar products because they identified a smaller difference in the burned area compared to other products. The products that stand out the most are MAPBIOMAS and MCD64A1 due to a difference of 90.62% between the burned-area mappings. Regarding land use, we observed that the products with higher resolution (GABAM and MAPBIOMAS) showed smaller differences in burned area mapping than the products with lower resolution (GWIS and MCD64A1). This difference can be observed in products with the same origin (Landsat 8), where the MAPBIOMAS identified a greater amount of burned area than GABAM, and registered more small burned polygons. Despite the greater area mapped mapping of the burned area, MAPBIOMAS may have registered a greater interference from noise and the contribution of small polygons. Reference data, such as ground truthing or higher resolution in images would be necessary to further evaluate this. Thus, between comparisons at a municipality scale, the data from GABAM, GWIS, and MCD64A1 were the most similar for mapping the burned area in the study region, despite differences in spatial resolution. The study can help to develop products for the burned areas detection on a local scale since the fusion of one or more products in a grid can produce data closer to the real burned area. However, here we tested for a local at the Amazon and the product performance may vary according to other ecosystems. It is desirable to have an independent burned area map, produced with detail and human editing for a more comprehensive quantification of the operational product strengths and limitations.

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